Upward Flame Spread on Composite Materials

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INTRODUCTION

The composite materials of interest in this work contain several plies of long, high strength fibers, typically woven in some fixed pattern; the layered multi-ply structure is embedded with an organic polymer resin. Such composites offer a high strength-to-weight ratio and other advantages, such as corrosion resistance, which make them attractive for a wide variety of structural uses. In particular, the U. S. Navy is investigating the use of such composites for both ship and submarine compartment construction; load-bearing compartment walls would consist of flat (or possibly more complex) panels of composite material.

In this or any other structural use of composites, one must be aware of two potential limitations brought on by the organic nature of the binder resin. Both are potential consequences of a fire in proximity to the composite. First, the primary role of the resin--to hold the fibers in place--may be compromised if it gets too hot. The result is that the composite loses its strength. This is particularly a problem for certain relatively inexpensive thermoplastic resins[1]. Second, the resins are typically flammable, though to varying degrees, and thus may contribute to the spread of a fire.

It is the second problem area which is addressed here. In particular, we are seeking a consistent way in which to characterize composite materials in small-scale tests so as to be able to predict their full-scale flammability behavior. The focus here is on upward flame spread because it typically represents the fastest mode of fire growth. Three existing models of this spread process are compared with data obtained in a vinyl ester/woven glass roving composite in an intermediate scale facility. As will be seen, certain modifications were necessary in the small-scale characterization of the composite by means of heat release rate calorimetry.

FLAME SPREAD MODELS

There are three key elements to any model of upward flame spread: (1) the variation of the flame heat flux as a function of distance ahead of the pyrolysis front, (2) the height of the flame as a function of the total heat release rate below the flame front and (3) the dependence of the heat release process from an element of ignited fuel on both external flux and time. The models examined here treat each of these differently. The simplest model, that of Cleary and Quintiere[2], assumes the flame heat flux to be spatially constant, the flame height to be a linear function of heat release rate below the front and the fuel heat release rate to be constant in time until complete consumption occurs at any given height on the fuel surface. These assumptions allow an analytical solution for pyrolysis front position versus time. The model of Mitler[3] is numerical in nature. It uses separate sub-models, grounded in data from gas burner experiments, to calculate radiative and convective flux from the flame versus height. The flame height correlation is also based on gas burner results. A transformation procedure is used to take fuel heat release data obtained at one external heat flux and convert it to any other arbitrary external flux. The model of Brehob[4] and Kulkarni, et al[5], also numerical, uses an experimentally-fitted exponential decay law for flame heat flux as a function of height and an experimental flame height correlation, also based on gas burner behavior, but different from that used by Mitler. Finally, this model uses experimental data at the specific external flux of interest for calculating heat release rate versus time.

In all of these models the chemistry of the fuel is subsumed into the heat release behavior and the ignition temperature. A behavior peculiar to composite materials, namely the tendency for the fiber plies to delaminate in response to gas generation between the plies, is not explicit in any of these models, nor is the high inert content.

EXPERIMENTAL

The intermediate-scale experiments were performed with the facility sketched in Figure 1. A flat, 0.95 cm thick composite panel (vinyl ester/glass), 0.38 m wide by 1.22 m tall, is uniformly irradiated ($\pm$ 5%) on one surface by a pair of electrically-heated panels. Irradiation is started at time zero by removal of a shutter; at the same time a methane-fueled line burner, spanning the sample width at its base, is ignited. This burner ignites the composite across its base initiating upward flame spread. The location of the pyrolysis front is noted by an observer at frequent intervals, to an accuracy of a few centimeters. Heat flux gages inserted through the sample at three heights aid in assessing flame fluxes. and appropriate conditions for small-scale assessment of heat release rate. Flame spread rate is measured, in separate experiments, as a function of both incident radiant flux and igniter heat release rate.

The Cone Calorimeter is used to measure heat release rate per unit area on 10 cm square samples of the composite. The sample is pre-heated with an external flux comparable to that used in the above experiments then a methane line burner below the sample is ignited. This burner produces a turbulent flame over the sample face resulting in a total heat input to the sample surface comparable to that in the intermediate-scale experiments. The heat release rate of the sample plus burner combination is recorded and the burner contribution subtracted to obtain the desired input data for the models. The accuracy is nominally $\pm$ 5% but the repeatability, especially at lower fluxes, was as poor as $\pm$ 25% in portions of the heat release history. This technique is unconventional; it is an adaptation of a procedure developed by Kulkarni[5] to get heat release data at external fluxes below that necessary to ignite a material.

RESULTS AND DISCUSSION

Figures 2, 3 and 4 show a comparison of typical experimental data against the three spread models examined here. The data shown for each flux are the result of two replicate tests. The input data characterizing the composite are the same for all cases. These data, particularly thermal properties, are problematical, however. The thermal conductivity was measured at about 100 °C for an undegraded composite sample and this is the value used here. One can readily argue that this value is approximate at best in this application. Ordinarily the conductivity is an increasing function of temperature but, as the resin begins to degrade and interply delamination occurs, the conductivity can be expected to drop. There is no quantitative data on these trends at present. The effective heat capacity also is not well-defined a priori; endothermic degradation reactions prior to ignition can increase it by an undetermined amount. Here, as a first step, this problem has been handled via an analysis of the ignitability behavior (ignition delay time vs. incident heat flux) of the composite. Ignition delay is dependent on the thermal inertia (product of conductivity, density and heat capacity). The effective value of thermal inertia is inferred by matching the experimental ignition data with an exact thermal model of the ignition process. Unfortunately, the effective thermal inertia obtained in this manner depends somewhat on the heat flux at which the match is made. Here a value of 1.4 times the nominal room temperature value is inferred from a match in the 20-25 kW/m^2 range. This multiplier is applied entirely to the heat capacity.

Fig. 2 shows a comparison between the data and the model of Cleary and Quintiere [2]. This model deals with sample heat-up in a simplified way and thus cannot correctly calculate the pre-heating of the sample as a function of height due to the external radiant flux. Instead we have calculated the pre-heat effect at mid-height using an exact model applied for a time up to the experimental arrival time of flame at that height. This initial temperature is applied to the entire sample. The model also simplifies the ignition process induced by the gas flame igniter at the

sample base. The flux is taken to be uniform over the igniter height and thus this full height ignites simultaneously yielding the vertical lines at the beginning of each model trace in Fig. 2. This model uses an average of the rate of heat release data for the given external flux; the averaging time interval is that required for the pyrolysis front to reach mid-height. Here that time was found iteratively by successive model solutions. In spite of all of these approximations (and others noted above), this model gives better quantitative agreement with the flamespread data than do the more mechanistically exact models discussed below.

Fig.3 shows a comparison of the data with the predictions of Mitler's model [3]. With the thermal properties described above, this model clearly predicts somewhat faster upward spread than is seen experimentally. It should be noted that neither this nor the preceding model predicts the "plateau" behavior seen at the lowest flux. That behavior appeared to be due to a partial delamination on the lower half of the sample only at about 325 seconds which caused an abrupt upward surge of flame spread. A larger igniter gas flow (2X) eliminated this plateau. Mitler's model starts out reasonably well for both fluxes but then over predicts the speed of full upward spread. It uses heat release data from an intermediate external flux (4 kW/m^2) transformed to the actual flux of interest. The predictions are somewhat different if heat release data from another flux are substituted implying that the transform method is only approximately applicable to this composite material.

Fig. 4 shows a comparison with the model of Brehob [4] and Kulkarni [5]; note the extended time scale. The heat release data are those measured at 4 kW/m^2 and 13 kW/m^2; data are not yet available at the run conditions of 2.5 and 11.5 kW/m^2. Such data would probably improve the agreement between model and experiment. This model does predict a plateau at the low flux though later than that seen experimentally. This model also incorrectly predicts a very short plateau at the higher flux. Since the model does not account for delamination which appeared to be the actual cause of the experimental plateau, its plateau mechanism requires further study.

All of the models can be brought into better agreement with experiment by adjustments of the effective thermal inertia of the composite. This has not been done here because no further data on thermal properties of this composite exist now. It appears that all of the models can be useful for engineering analysis of flame spread hazards of composites.

ACKNOWLEDGEMENTS

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FIG. 1 NIST RADIANT PANEL FACILITY

FIG. 2 — MODEL OF CLEARY & QUINTIERE [2] VS EXPERIMENTAL DATA

FIG. 3 — MODEL OF MITLER [3] VS. EXPERIMENTAL DATA

FIG. 4 — MODEL OF BREHOB [4] AND KULKARNI [5] VS EXPERIMENTAL DATA